



In-situ measurements of sound propagating over extensive green roofs

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ABSTRACT

In this study, in-situ measurements of sound propagating over flat, extensive green roofs are presented for 5 cases. Measurements were performed just before and just after the placement of the green roof (under dry conditions) with an identical source-receiver configuration in both situations, allowing a direct estimate of the acoustical effect. Situations involving a single and double diffraction over the green roof were considered, for substrate thicknesses ranging from 20–30 mm to 180 mm, and for vegetation cover ranging from absence to 100%. The green roof acoustic effect was analyzed for propagation path lengths interacting with the roofs ranging from 2.5 m to 25 m. Measurements show that green roofs might lead to consistent and significant sound reduction at locations where only diffracted sound waves arrive relative to common, non-vegetated roofs. A single diffraction case with an acoustic green roof improvement exceeding 10 dB was found for sound frequencies between 400 Hz and 1250 Hz, although the green roof interaction path length was only 4.5 m. For less shielded receivers, a change in interference pattern might be observed, leading to positive or negative effects, relative to a non-vegetated roof top. For the double diffraction cases the green roof improvement is less frequency-dependent and a case with positive effects up to 10 dB was found.

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1. Introduction

The ecological and economic advantages of green roofs have been well-recognized. Scientific studies focus mainly on thermal insulation, energy consumption of buildings and reduction of urban heat island effects [1–8], rainwater runoff management [9–12], air quality improvement and increased carbon dioxide uptake [13,14], increasing biodiversity in an urban environment [15–17], and economic and environmental life cycle assessment [18–21].

Only very recently, scientific research to the acoustical effects of vegetated roof tops is conducted. Basically, sound can be reduced by a green roof in two ways, namely by providing increased insulation of the roof system and by absorption of sound waves diffracting over roofs.

A straightforward effect is the decreased sound propagation through the roof system to the inside of the building. This effect was studied experimentally under controlled conditions by means of a small box equipped with a semi-extensive green roof in Ref. [22]. This application of green roofs is rather limited. The presence of noise sources above roof level is uncommon, unless air traffic is considered. Nevertheless, only in a very dense building setup

positive effects can be expected, since in such situations sound is nearly normal incident on the roof during a complete passage. For detached buildings, the effect of a green roof on noise exposure from overflying air traffic is expected to be limited when considering time-integrated sound levels.

The material properties of objects over which sound diffracts play an important role. Hadden and Pierce proposed an accurate analytical solution for sound diffraction near wedges [23]. This method is often referred as the four-ray diffraction model since 4 terms appear in their analytical solution. Three of these terms are associated with the absorption characteristics of the faces constituting the diffracting object. One term uses the properties of the face at the source side, another term the properties of the face at the receiver side, and a third term is influenced by both faces. Calculations in Ref. [24] show a large decrease in sound pressure level at a partly absorbing right angle, relative to a fully rigid one. With increasing distance between the diffracting edge and receiver, such effects become more pronounced. Furthermore, when receivers are located close to the surface, or in case of double diffraction (e.g. sound propagation over a rectangular building), the angle of incidence is near parallel to the absorbing material. As a result, the absorption of sound waves increases significantly [25].

The typical green roof substrates have interesting sound absorbing properties. Growing mediums used in green roofs are highly-porous, and allow acoustic waves to enter the medium,

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which is a necessary property of a sound absorbing material. Due to the large number of interactions between the waves and the solid phase of the substrate attenuation occurs.

These theoretical considerations are consistent with the numerical calculations in Refs. [26,27], showing the high potential of green roofs in reducing diffracting sound waves over it, compared to (acoustically) rigid roofs, for various building and roof types. The importance of parameters like the surface area covered with green roof substrate, the substrate depth of both intensive and extensive green roofs, and uniformity of the calculated effects along the shielded façades were studied.

Although the presence of an obstacle like a building or house induces a high degree of shielding, sound levels can still be high at shielded locations near street canyons (with dense road traffic), due to the large number of reflections in between the building façades forming the street. Such street canyons are however common in many city centres. Furthermore, the presence of a silent courtyard or façade was identified as important based on large scale noise annoyance surveys [28,29]. A quiet side allows people to organize their homes and to place noise-sensitive rooms at the silent façade, or to benefit from the mental restoration found in silent courtyards in an otherwise noisy environment.

However, experimental data with relation to sound propagation over green roofs is lacking. The numerical simulations in Refs. [26,27], although using a state-of-the-art full-wave numerical technique, involved some idealizations. Firstly, only a homogeneous growing substrate was modeled. Secondly, the parameters to describe the acoustic properties of the granular substrate in the simulations were derived from literature reports of equivalent materials.

Good green roof practice, on the other hand, involves various layers, each with a specific purpose. A typical build-up is as follows. A root barrier membrane is needed if the roof finishing might be penetrable by plant roots. Next, a drainage layer is needed to evacuate excess water. This could be a gravel-like material or a profiled synthetic fabric. The latter often contains small water reservoirs in order to allow water to evaporate and penetrate the substrate in periods of drought. Another advantage of such a profiling is to prevent acidification of the substrate by easily allowing air to enter from below. Next, a geo-textile or filter membrane is placed, mainly to prevent substrate loss. This layer is topped by the granular growing medium. The thickness of the substrate depends on the plant needs and is also limited in practice by the weight allowed by the roof construction (taking into account periods of water saturation in the green roof layers). A mineral, highly water absorbing fabric like rock-wool might be placed just below the substrate to largely increase water retention. Finally, a vegetation layer is present. Depending on the species choice and on location-dependent parameters (like roof construction and climate), adaptations to the succession of these layers can be made and appropriate layer thicknesses should be chosen. It is clear that the acoustical effects of such choices might strongly influence the sound absorption property of the roof system as a whole.

In this study, in-situ measurements of the effect of extensive green roofs are presented. It is intended to show what can be expected from current green roof practice in Flanders (Belgium), for sound diffracting over it, for various building configurations. Measurements were performed just before and after placement of the green roof, with an identical source-receiver configuration in both situations. In this way, the green roof effect can be directly estimated, since the only difference between the two measurements was the presence of the green roof.

The paper is organized as follows. In Section 2, the measurement methodology and instrumentation is described. In Section 3, the different cases are presented. In Section 4, results are discussed and finally conclusions are drawn in Section 5.

2. Measurement methodology and instrumentation

In this study, portable and battery-driven equipment was used. In this way, the operator has full flexibility to choose source and receiver locations at the measurement sites.

An alarm gun (Bruni mod. 92, with 8 mm blanks) was used as acoustic source. The use of such a noise source is common in room acoustic applications, and is sometimes used in (outdoor) sound propagation experiments. A main advantage of such a device is the emission of high sound levels which makes a shot easily identifiable even at locations with high background noise levels. Furthermore, an acoustic pulse is produced which contains a wide range of sound frequencies. An alarm gun is also a good approximation of a point source, especially at lower frequencies. Lastly, it is highly mobile and independent of external power.

The reproducibility of successive shots produced by the gun was checked in a full anechoic chamber. Five shots were released at 4 m from the microphone. The averaged recorded spectrum (1/3 octave bands) is shown in Fig. 1. At 100 Hz, a sound pressure level of 73 dB was measured. At 1 kHz the maximum level in the spectrum is obtained, exceeding 100 dB. Up to 10 kHz, the levels stay above 90 dB. At low frequencies, levels are rather limited. Nevertheless, it is expected that these frequencies are only affected to a limited degree by a green roof substrate. Furthermore, these long wavelengths are shielded to a limited degree only, yielding sufficiently high levels after being diffracted. The size of the error bars drawn at each frequency equals 2 times the standard deviation. Both at low (<100 Hz) and high frequencies (>2500 Hz), the standard deviations are near 2 dB. For the intermediate frequencies, this value is between 0.5 dB and 1 dB. It can therefore be concluded that the reproducibility at each 1/3 octave band is sufficient by emitting a series of 5 shots.

The measurements were performed with a ½" electret microphone (type MK 250 B, Microtech Gefell) with a sensitivity of 44 mV/Pa, connected to a pre-amplifier (type SV 12, Svantek). The microphone capsule has a flat frequency response over the full audible frequency region, and deviations are less than 1 dB up to 15 kHz for normal incident sound. The saturation level exceeds 140 dB (at 1 kHz) and is sufficiently high for the envisaged application.

The logging of the measurements was done with a Svantek 959 handheld device. Results were logged as 1/3 octave bands every 10 ms. Before each measurement, the full measurement chain was

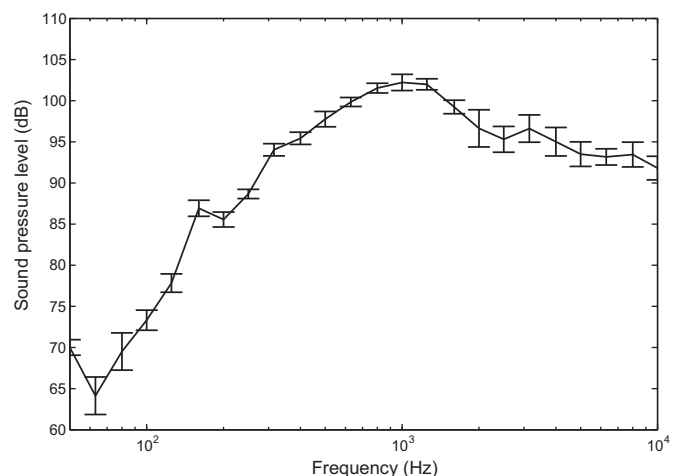


Fig. 1. Sound level spectrum in 1/3 octave bands produced by the alarm gun in the anechoic chamber (at a distance of 4 m). The error bars at each frequency are based on 5 repetitions and have a length of 2 times the standard deviation.

Table 1

Overview of green roof parameters and some experimental data in the various cases considered. Product details, when available, were provided by the manufacturers (and are not based on on-site measurements).

Test case number	Location	Reference roof coverage	Green roof built up and layer thicknesses	Propagation path length interacting with green roof	Vegetation coverage (%)	Green roof age (since placement)	Cumulative rainfall	Measurement date (with green roof)
1	Groendreef, Gent	Concrete + bitumen cover (roofing)	1. Root barrier membrane 2. Water retention mat (rock-wool) (50 mm) 3. Substrate: combination of synthetic fibres and light mineral substrate (20–30 mm) in big tiles 4. Vegetation layer: combination of various Sedum species and mosses	8 m	>75%	7 days	5 mm (last 7 days), 0.3 mm (last 5 days)	September, 10 (2009)
2	Achilles Musschestraat, Gent	EPDM	1. Root barrier membrane 2. Profiled drainage layer from EPS with water reservoirs (16 l/m ²) (62 mm) 3. Filter fleece (230 g/m ²) 4. Granular substrate (of 0.9 kg/dm ³ in dry conditions) (50–60 mm) 5. Vegetation layer: sparse sedum shoots	2.5 m (+1.5 m wooden terrace)	<5%	9 days	1 mm (last 9 days), 0 mm (last 5 days)	July, 2 (2009)
3	Distelstraat, Gent	EPDM	1. Root barrier membrane 2. Profiled polystyrene water drainage layer including waterreservoir of 18 l/m ² (62 mm) 3. Filter fleece from polypropyleen (180 g/m ²) 4. Mineral substrate: combination of turf, porlith and mixture of small stones, sand, etc. (particles sizes between 0 and 12 mm) (180 mm) 5. Vegetation: various types of grasses	4.5 m (+ 0.2 m stones)	50%	188 days	10 mm in last 30 days, 0 mm (last 5 days)	May, 25 (2010)
4	Rodelijvekensstraat, Gent	Concrete + 4 mm bitumen layer	1. Root barrier membrane (200 g/m ²) 2. Substrate (mineral puzzolaan + organic compounds) (30–40 mm) in prefabricatd cells (made of polyethyleen with dimensions of 330 mm on 330 mm) 3. Vegetation: sedum plants	25 m (+1 m stones)	>90%	22 days	83 mm (last 22 days), 0 mm (last 5 days)	June, 4 (2009)
5	Oudstrijderstraat, Blankenberge	EPDM	A. Flat roof see 3.1–3. 4. see 3.4, thickness here 80 mm 5. sedum shoots B. Sloped part (about 50°) see 3.1–3 4. see 3.4, now inside a cellular confinement system, thickness here 100 mm 5. sedum shoots	25 m (flat roof part)	<5%	7 days	3 mm (last 7 days) - 2 mm (last 5 days)	May, 20 (2010)

calibrated with a Bruel & Kjaer 124.06 dB pistonphone, producing a pure tone of 251.2 Hz. A professional weather proof outdoor unit (WME 950, Microtech Gefell) was used, including a wind screen to prevent possible wind-induced microphone noise. The microphone was attached to a telescopic tripod.

3. Description of the test cases

In this study, 5 test cases are considered. Performing such measurements is quite demanding from an organization point of view. Most cases involved new buildings or new building parts. An important condition to perform this type of measurements was that the green roof was placed once the outer building envelope was fully finished (e.g. including windows and doors). The building setup in the surroundings of the green roof under study must be

identical as well in both measurements (like e.g. ground levels and ground cover, new buildings, etc.). These conditions were fulfilled in the 5 cases presented in this paper.

The main goal of this research is to show what effects can be expected for sound diffracting over green roofs in realistic situations. In most cases described here no acoustic benefits could be expected for the inhabitants, given the absence of an important environmental noise source at the location of the gunshot. Nevertheless, the measurements presented here involve cases with single and double diffraction over a green roof as in situations where the source-green roof-receiver geometry allows actual noise reduction. Two interesting cases were already presented in Ref. [27]. The first situation involves a building extension with a green roof where sound is forced to be diffracted over it (shearing sound propagation over the green roof) before reaching a façade or window (single

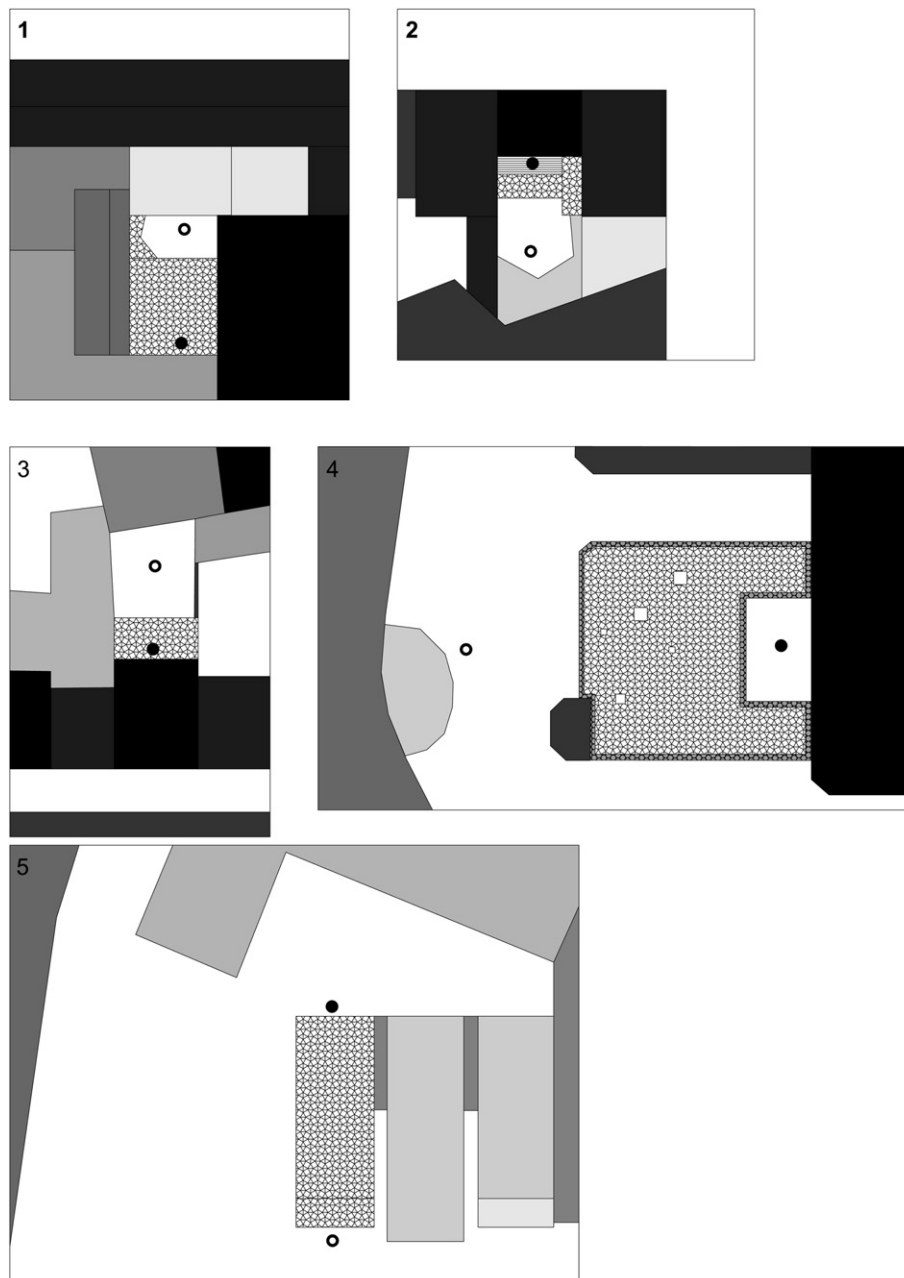


Fig. 2. Plan views of the measurement locations. The green roof is indicated by the structured pattern. The grey scale is proportional to the building heights in the surrounding of the experimental sound propagation path. The receiver position is shown with the filled black circle, the location of the acoustic source with the open circle.

diffraction). The second situation aims at achieving a silent zone at a non-directly exposed façade while the source is in an adjacent street canyon. In the latter, the green roof was modeled on the main part of the building (double diffraction).

All test cases have extensive green roofs with a rather limited substrate thickness, applied to flat roofs. The cases were not selected on such a basis, but this shows the popularity of this type of vegetated roof tops. An overview of the green roof parameters in the various cases can be found in Table 1. Both prefabricated green roof tiles (cases 1 and 4) and dumped substrate at the location

(cases 2, 3 and 5) were found. The substrate thicknesses ranged from 30 mm to 180 mm. The vegetation cover ranged from absence of vegetation (only sparse sedum shoots visible) to full cover. Most popular are the sedum green roofs. In case 3, various types of grasses were present. The measurements in presence of the green roof were mainly performed very shortly after its placement, to ensure identical situations in the before and after measurements. Case 5 involves a rather uncommon sloping part equipped with a green roof, to integrate the greenery on the roof to an adjacent small park. Given the large slope (near 50°), a cellular confinement

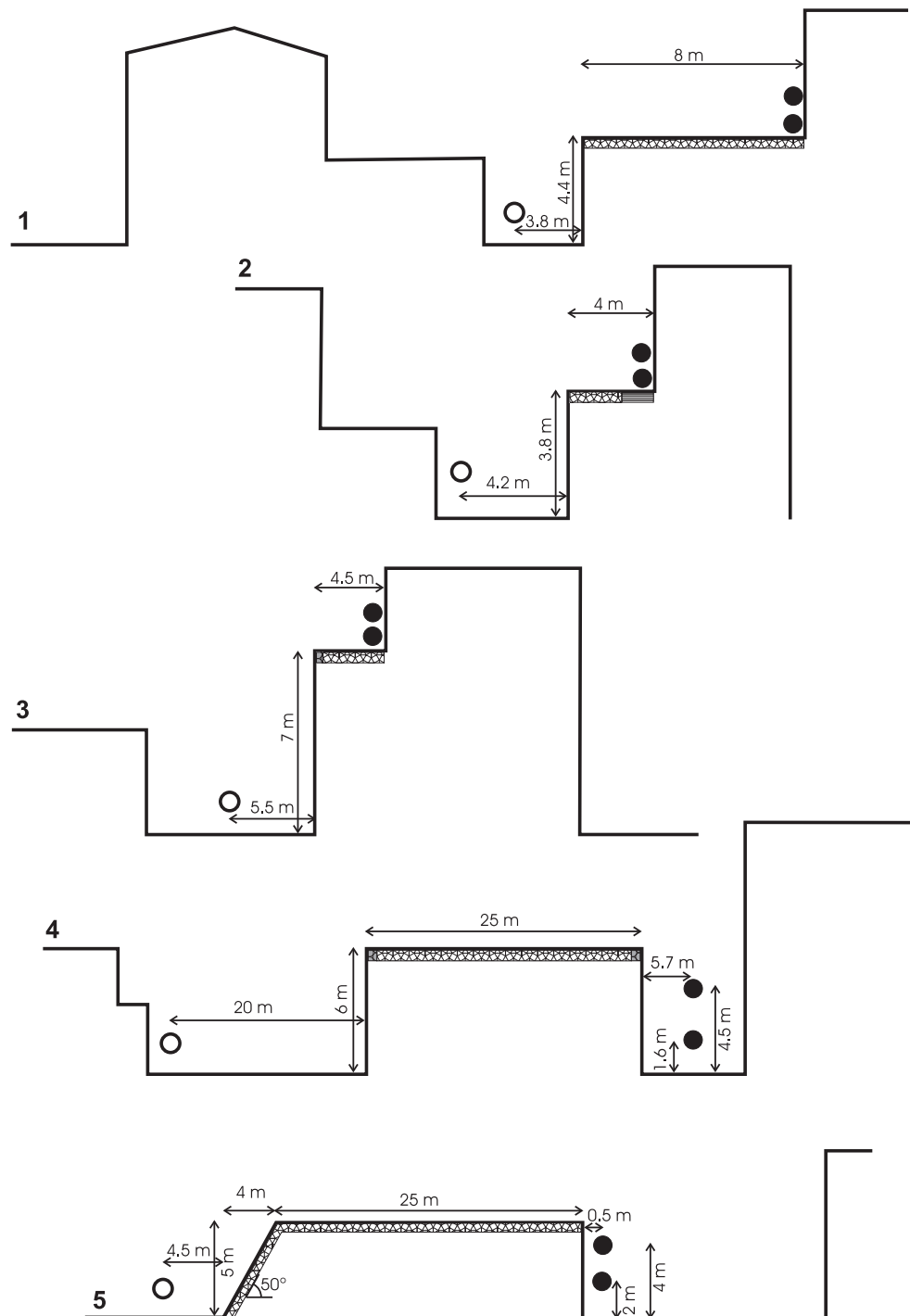


Fig. 3. Cross-sections and dimensions of the sound propagation paths. The receiver positions are indicated with the filled black circles, the location of the acoustic source with the open circle. In cases 1–3, receiver heights are 0.3 m and 1.9 m, while the microphones are placed less than 0.1 m from the façades. The source height is 1.6 m in all cases.

system was applied to this part to prevent substrate loss. At this location, the substrate thickness was 20 mm larger compared to the flat green roof part.

Most measurements were performed after rather dry periods. As an indication, the cumulative rainfall in the last 30 days (if applicable) and in the last 5 days is shown in Table 1. Only in case 4, a large amount of rainfall was measured since placement. However, no rainfall was measured during the 5 days before the acoustical measurement in the presence of the green roof.

For the reference situations (before the presence of the green roofs), two types of roof finishing were found among the test cases namely bitumen cover on concrete (roofing) and EPDM. These materials are very common as the outer layer for non-vegetated roof tops as well. So the reference situation considered in the experiments is representative for current practice of non-green flat roofs.

In Figs. 2 and 3, schematic plan views and cross-sections of the propagation paths can be found for the 5 test cases. There is no direct view (or straight sound propagation path) between source and receiver. The 5 cases considered can be categorized in two groups, having either a single or double diffraction. In cases 1–3, a single diffraction is needed to reach the receiver. Cases 4 and 5 involve diffractions at two roof edges. In all situations, two receiver heights were considered, and a single source location.

In cases 1–3, the sound propagation path is fully bordered by high buildings. The receivers are placed very near to the building façade (less than 0.1 m) to maximize the sound propagation path

length over the green roof part. Reflections in the source-receiver plane (e.g. at the façade near the microphone, or at the buildings behind the source) could influence the sound pressure level at the microphone. Detailed analysis shows that only after a large number of reflections, it is possible for sound to reach the receiver without diffracting over the green roof, e.g. in cases 1 and 2. However, the contribution of such sound rays to the total level received at the microphone is limited since the increased length of such sound paths leads to a large amount of energy loss by geometrical spreading. In case a dominant sound path diffracting over the non-green roof is largely attenuated by the presence of the green roof, the importance of such later reflections could be increased. If this should be the case, measured results could be an underestimation of the green roof effect. This is consistent with the conservative approach when proving effects in scientific research. Nevertheless, such effects are expected to be of limited importance.

Case 4 involves sound propagation to a fully shielded courtyard, and only diffracted waves over the green roof could reach this area. In case 5, reflections on the façades on the far left row of buildings cannot be excluded. To minimize their importance, the source and receivers were placed very close to the green-roofed building, so at least one diffraction around a vertical edge is needed for such sound paths. Double diffraction around the vertical edges could be present as well (which is sound propagation around the building, so without interaction with the roof). This effect is minimized by placing the source and receiver very close to the building part under study, and by positioning the microphone at a higher level

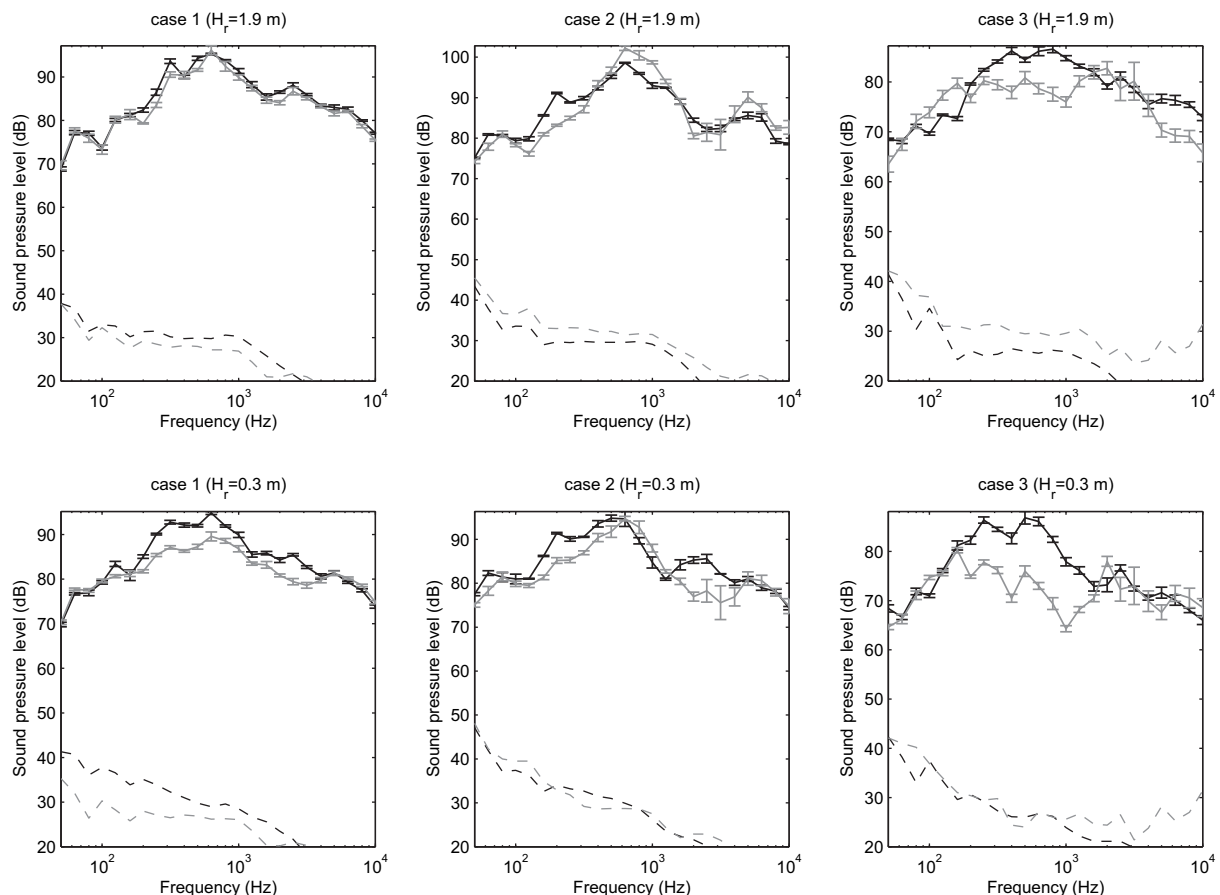


Fig. 4. Measured sound pressure level spectra in 1/3 octave bands (for cases 1–3) in absence (black full lines) and presence (grey full lines) of the green roof, for identical source-receiver geometry in both situations. The dashed lines represent the background sound pressure levels exceeding 90% of the time during the measurement in absence (black dashed lines) and presence (grey dashed lines) of the green roof. The error bars at each 1/3 octave band have a length of 2 times the standard deviation. In the upper row, the higher receiver locations are considered, in the lower row the lower receiver locations. H_r means receiver height relative to the roof level.

than the source position. In this way, the diffraction angles between the horizontal roof edge and the receiver is smaller than the diffraction angle between the vertical edge and the receiver (which is near 90° here). This makes the diffraction around the vertical building edge less intense.

Part of the sound propagation paths interacting with the green roofs ranged from 2.5 m to 25 m. In case 2, the green roof part near the edge of the roof was followed by a wooden terrace of about 1.5 m when going from source to receiver. In cases 3 and 4, the roof edges were bordered with a layer of small stones, of respectively 0.2 m and 1 m.

4. Measurement results

In Figs. 4 and 5, the measurement results are shown for the various cases described in Section 3. The measured sound pressure levels are expressed in 1/3 octave bands, and are shown for both the situation with and without the green roof. The background noise level spectrum (levels that were exceeded 90% of the time in a time frame of 2 min centered around the releases of the 5 shots) at the microphone during both measurements is shown as well. In Fig. 6, the relative effect of the green roofs is shown. Positive values indicate that green roofs provide noise reduction. Cases 1–3 and cases 4 and 5 were grouped; separate plots were made for the low microphone height and the more elevated microphone position in both groups.

Comparing the background noise levels to the levels produced by the alarm gun shows that the in-situ signal-to-noise ratio (SNR) is very high. The minimum SNR observed is near 10 dB in case 4 for frequencies near 100 Hz. Sound pressure levels lower than 20 dB (at individual frequencies) are not presented. At 1 kHz, the SNR in the single diffraction cases (1 to 3) easily exceeds 50 dB, for the double diffraction cases (4 and 5) 30 dB is achieved.

In case of the single diffraction cases (1–3) and a receiver height of 1.9 m (above the roof level), frequency bands with pronounced positive and negative effects are observed for cases 2 and 3. In case 1, effects are either slightly positive (up to 4 dB) or no effect relative to the reference roof is seen. For the low receiver heights (0.3 m above roof level), the green roofs give important acoustical benefits. Negative effects are nearly not present here, except for case 2 in the frequency range from 800 Hz to 1250 Hz, where mean values up to -3 dB were measured. In case 1, improvements near 5 dB are obtained in the broad frequency range from 250 Hz to 3150 Hz. In case 3, this zone with consistent positive noise reduction is somewhat less broad (now between 125 Hz and 1250 Hz), but values are significantly higher, exceeding 10 dB between 400 Hz and 1250 Hz. The thick substrate layer of 180 mm is probably responsible for this large effect. At high frequencies (above 5 kHz) there is no net effect by the presence of the green roof. Note that also for these higher frequencies, the measured levels are much higher than the background noise levels (see Figs. 4 and 5).

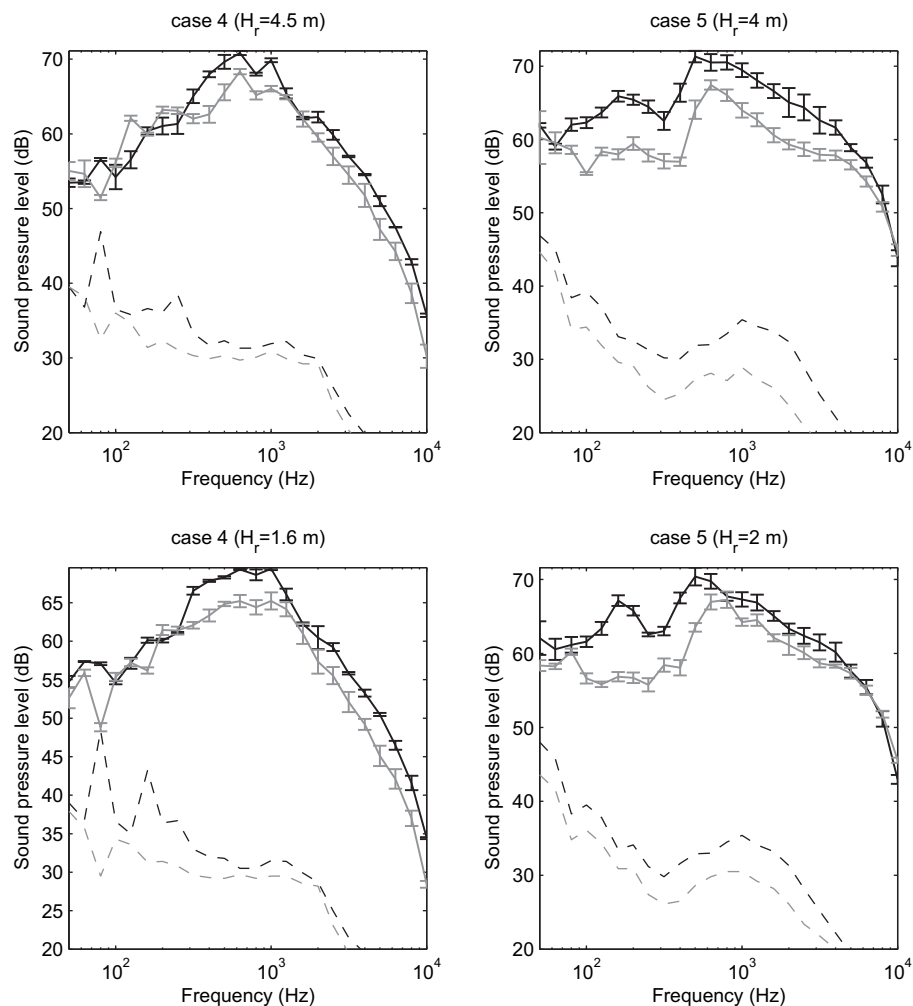


Fig. 5. See caption of Fig. 4. Results for cases 4 and 5 are depicted now. H_r means receiver height relative to ground level.

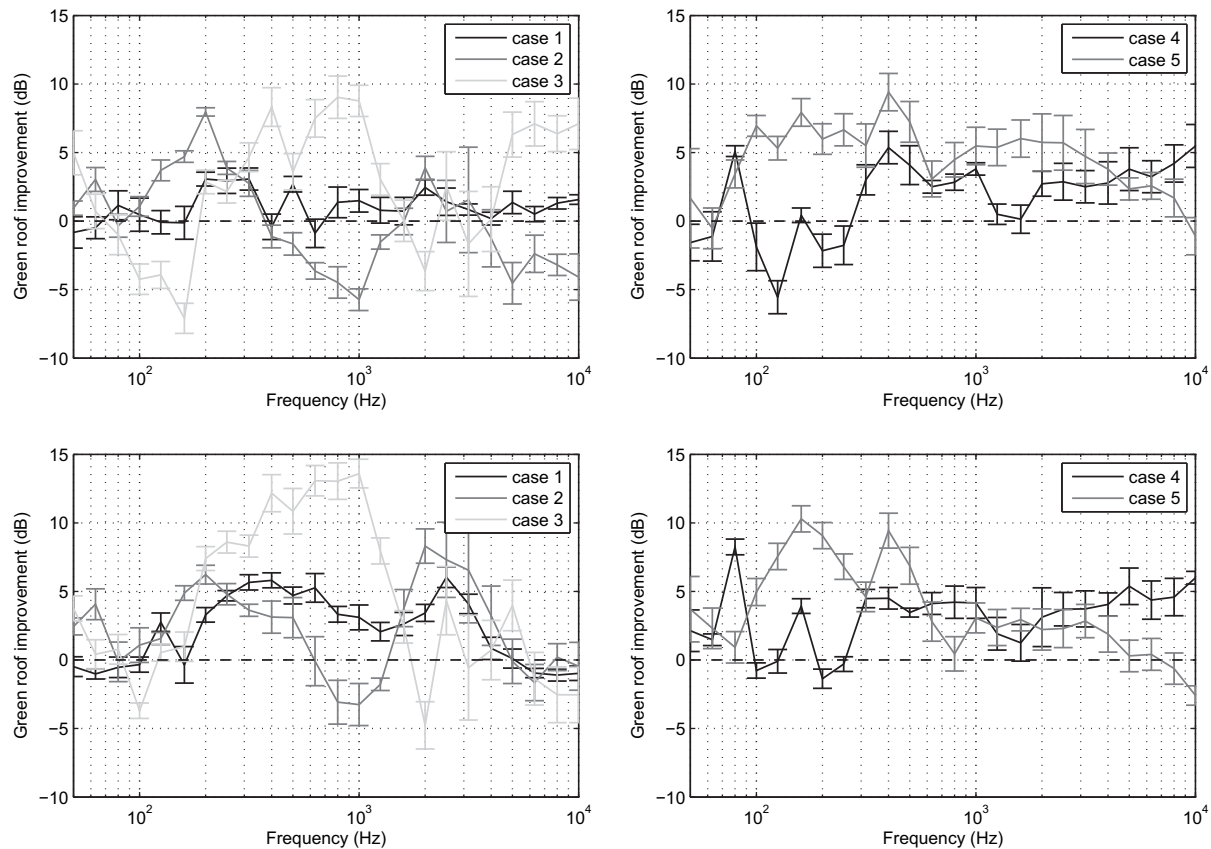


Fig. 6. Green roof improvement spectra for the various cases considered in this study. In the upper row, the high receiver locations are considered, in the lower row the low receiver heights. The error bars at each 1/3 octave band centre frequency have a length of 2 times the standard deviation.

The succession of pronounced negative and positive effects for cases 2 and 3 for the 1.9 m receiver height is most likely caused by a shift in the interference pattern due to the change in roof cover. Quantitative or even qualitative prediction is difficult, since it involves (partly) diffracted sound, and various reflections at the interfaces between the different layers constituting the green roof. Furthermore, there is also an impedance change in horizontal direction, caused by the presence of the wooden terrace in case 2 near the façade, and by the presence of a limited zone of small stones in case 3 near the flat roof edge. For the low receiver height, such interferences are less pronounced. This leads to more consistent acoustical green roof improvements over the full frequency range, mainly in case 1 and 3. For case 2, interference effects are still present, probably caused by the very short propagation path. To assess the importance of such positive and negative green roof effects at particular frequency bands, one has to take into account the dominant noise spectrum in a specific application.

For both the high and low receiver in case 1, sound is diffracted to a large extent since the source is located close to the green-roofed building, and the propagation path over the roof is 8 m (so much longer than in cases 2 and 3). Therefore, interference patterns are not observed at both the high and low receiver. The acoustical effect is nevertheless much more limited at the higher microphone position than at the lower one in case 1. It is well-known that when the angle of incidence (or the angle of reflection) goes from orthogonal to near parallel relative to a porous material, the absorption of sound waves increases significantly [25]. For the higher receiver height, the angle of reflection (after diffraction at the roof edge) on the roof is higher and therefore a smaller green roof improvement is obtained.

For the double diffraction cases (4 and 5), roof lengths are much longer compared to the single diffraction cases. The receivers are now fully in the acoustic shadow zone formed by the building. Only shearing waves over the roofs can reach the microphones. In case 4, a pronounced negative effect at 125 Hz is nevertheless observed. Starting from 300 Hz, consistent positive effects are observed between 0 dB and 5 dB. Also at the highest frequencies considered, the 10 kHz 1/3 octave band, a green roof improvement of 5 dB is observed. Case 5 gives consistent improvements over the full frequency range, starting already from 50 Hz. Between 100 Hz and 3150 Hz, the improvement by the green roof is between 5 dB and 10 dB. Compared to case 4, a decrease in performance with increasing frequency, starting from 3 kHz, was measured. The frequency-dependence of the acoustic effect of the green roof seems to be less present compared to the single diffraction cases.

The green roof improvement at the higher microphone position in case 4 is similar to the improvement at the lower microphone position. From numerical simulations it is known that the relative effect of a sound reducing measure is rather location independent in such a closed courtyard [30]. The exact height of the microphone is therefore less important when looking at the acoustical green roof improvement. At the lower microphone, however, negative effects are nearly not present anymore.

For case 5 at the lower microphone height, effects become much more limited from 2 kHz on compared to the higher microphone level.

The positive effects at higher frequencies in case 4 could be qualitatively related to the limited substrate thickness of only 30–40 mm. This effect was shown in detail with the numerical calculations in Ref. [26]. Depending on the sound frequency, a maximum shielding by the green roof was observed in function of

substrate thickness. This maximum became more pronounced and shifted to smaller thicknesses with increasing frequency. Another possibility for this positive high-frequency behavior is the presence of low vegetation in case 4 in contrast to the absence of vegetation in case 5. Multiple scattering by plant material for shearing waves over the roof could limit high-frequency sound at the receiver. The relative importance of both effects is hard to assess from the current data.

5. Conclusions and discussion

In this study, in-situ measurements of sound propagation over flat, extensive green roofs were presented in 5 case studies. These involved situations with either a single diffraction or double diffraction over green roofs. Measurements were performed just before and just after placement of the green roof (in dry conditions), with an identical source-receiver configuration in both situations. In this way, the green roof effect can be directly estimated. The reference roofs considered in the experiments (roofing or EPDM) are representative for current practice of non-greened flat roofs. Substrate thicknesses ranged from 20–30 mm to 180 mm, while the propagation paths interacting with the green roof ranged from 2.5 m to 25 m. The vegetation cover ranged from absence of visible plant material to full cover. As an acoustic source, an alarm gun was used. The reproducibility of successive shots was confirmed by measurements in a full anechoic chamber. The standard deviation at frequencies between 100 Hz and 2500 Hz was lower than 1 dB for 5 successive shots. The in-situ signal-to-noise ratio in the single diffraction cases exceeded 50 dB (at 1 kHz), and was still as high as 30 dB (at 1 kHz) in the double diffraction cases.

Measurements show that green roofs may lead to consistent and significant sound reduction at locations where only diffracted sound waves arrive. Among the single diffraction cases, acoustic green roof improvements exceeding 10 dB were found, over a wide frequency range. This improvement was measured for a propagation path interacting with the green roof of only 4.5 m. The presence of shearing waves over the green roof (near parallel sound propagation to the roof), and sufficient substrate thickness seemed to be important to have such large positive effects. In situations with higher elevated receivers (less shielded receivers), a change in the interference pattern might be observed, leading to positive or negative effects, relative to a non-vegetated roof.

For the double diffraction cases, positive effects were measured over the full frequency range from 50 Hz to 10 kHz, at the two fully shielded receiver heights considered in the experiments. Effects seem to be less-frequency dependent than for the single diffraction cases, and a case with positive effects up to 10 dB was found. A small substrate thickness and/or the presence of vegetation seems to be positive for higher frequencies, while for low frequency noise reduction a larger substrate thickness is needed.

As shown in Table 1, the measurements were performed after rather dry periods. It is well-known that porous materials and outdoor ground surfaces can be largely affected by the presence of water [31,32], usually leading to a decreased sound absorption. Furthermore, the typical substrates for vegetated roof tops are known for their high water retention capabilities. The volume of the substrate particles will increase largely by absorbing water, leading to a decreased porosity of the substrate layer. Furthermore, the presence of water reservoirs or the use of rock-wool mats to further enhance water retention is probably not optimal from the view point of both sound reduction and thermal insulation. On the other hand, such layers could largely improve these aspects under dry conditions.

Detailed acoustical characterization of the various layers constituting a green roof could lead to a better understanding and

optimization of the sound reduction capabilities. It was already mentioned that the succession of such layers leads to complex acoustical behavior. Care is however needed that the non-acoustical beneficial effects of a green roof are preserved, and a compromise between conflicting demands might be needed (e.g. sufficient water retention versus sound absorption and thermal insulation).

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